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COMMENTS ON THE DOUBLY ASYMPTOTIC APPROXIMATION II. A SIMPLE APPROXIMATION FOR CUTOFF VELOCITY

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A model problem is used to examine the error of a simple approximation, obviating the calculation of relief pressures used in the Doubly Asymptotic Approximation. The error is a function of a quantity which may be interpreted as the ratio of structural response times to fluid pressure decay times. The greatest relative error is about 27% and usually is somewhat less, suggesting the use of a simple "correction factor" for cutoff velocity.

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FOREWORD

This work represents part of six man-months of effort, the ultimate objective of which is the direct prediction of the onset and details of submarine pressure hull rupture caused by underwater explosive attack. The immediate objective of this work is to consider an approximation offering some hope of circumventing the difficulties of applying the Doubly Asymptotic Approximation (DAA), an important but limited analytical tool for treating fluid-structure interaction in cases involving acoustic shock waves impinging on underwater structures.

J. F. PROCTOR
By direction

CONTENTS

ILLUSTRATIONS

INTRODUCTION

The Doubly Asymptotic Approximation, as implemented in USA-STAGS, has been successfully used to model fluid-structure interaction in a number of studies of the response of underwater structures to explosions. Unfortunately the USA implementation of the DAA appears to embody an utterly unrealistic feature according to which negative fluid pressures arise and exert a kind of suction force on the structure. In fact, the DAA should only be applied up to the time at which the total pressure becomes zero. Furthermore, this time occurs extremely rapidly in typical explosion loading situations.

In this report we consider a simple approximation to the DAA, which takes advantage of the rapid pressure cutoff.

MODEL PROBLEM

We consider a plane acoustic wave impinging on an infinite unrestrained air-backed plate of mass m per unit area, as illustrated in Figure 1. The incident pressure is subject to decay typical of underwater explosions:

$$p_I = p_o \exp(-t/\theta).$$

The total pressure on the plate is the sum of the incident pressure, the reflected pressure, and the relief pressure arising from plate motion:

$$p_T = p_I + p_R + p_r. \qquad (1)$$

The DAA uses the approximation [1]

$$p_R = p_I \qquad\qquad p_r = -\rho c v$$

where ρ is the water density, c is the acoustic wave speed in water, and v is the plate velocity. The equilibrium equation becomes

$$m\frac{dv}{dt} = p_T$$
$$= 2p_o \exp(-t/\theta) - \rho c v \qquad (2)$$

Now using the dimensionless quantities

$$w = v/c \qquad \tau = t/\theta$$
$$\kappa = \rho c\theta/m \qquad \nu = 2p_o\theta/cm$$

equation (2) is rewritten as

$$\frac{dw}{d\tau} + \kappa w = \nu \exp(-\tau) \qquad (3)$$

Equation (1) is called the Doubly Asymptotic Approximation since it is expected to give correct answers for very short and very long times.

The further simplification to be studied in this report is to neglect relief pressure except for determining the cutoff time and velocity. The rationale underlying this approximation is illustrated in Figure 2. Owing to plate inertia, appreciable plate motion and therefore appreciable relief do not occur until some time has passed. But by this time the major part of the pressure decay is likely to have occurred. If so, the cutoff pressures κw_r calculated using relief and κw_N without relief both intersect the curve for incident plus reflected pressure in the flat part of this curve. In this event, the difference between the intersection values of κw_r and κw_N should be small.

CASE 1: RELIEF PRESSURE RETAINED

With the initial condition $w(o) = o$, the solution of (3) is

$$w = \frac{\nu}{1-\kappa}\left[\exp(-\kappa\tau) - \exp(-\tau)\right] \qquad (4)$$

Cutoff occurs when

$$\rho c v = 2p_o \exp(-t/\theta)$$

and hence when

$$\kappa w = \exp(-\tau). \tag{5}$$

Substituting (5) and (4) and solving for the cutoff time τ_c leads to

$$\tau_c = -\ln(\kappa^{\frac{1}{1-\kappa}}) \tag{6}$$

The cutoff velocity w_r is now

$$w_r = \frac{\nu}{\kappa} \exp(-\tau)$$
$$= \nu\,\kappa^{(\frac{1}{1-\kappa})}$$

CASE 2: NEGLECT RELIEF PRESSURE EXCEPT AT CUTOFF

In this approximate treatment the relief pressure in the governing equation is neglected, leading to

$$\frac{dw}{d\tau} = \nu \exp(-\tau)$$

with the solution

$$w = \nu(1-\exp(-\tau))$$

Now cutoff still occurs when the actual relief pressure causes the total pressure to vanish;

$$\rho c v = 2p_o \exp(-t/\theta)$$

giving

$$\kappa w = \nu \exp(-\tau)$$

The cutoff time and velocity are now

$$\tau_c = -\ln(\kappa/(1+\kappa))$$

$$w_N = \nu/(1+\kappa)$$

The cutoff times and velocities are illustrated in Figure 2 for the cases with and without relief.

COMPARISON OF ACTUAL AND APPROXIMATE CUTOFFS

To measure the error of neglecting relief, we form the ratio w_r/w_N:

$$w_r/w_N = (1 + \kappa)\kappa^{\left(\frac{\kappa}{1-\kappa}\right)} \equiv \phi(\kappa)$$

The limiting behavior of $\phi(\kappa)$ is as follows:

$$\lim_{\kappa \to 0} \phi(\kappa) = 1$$

$$\lim_{\kappa \to \infty} \phi(\kappa) = 1$$

$$\lim_{\kappa \to 1} \phi(\kappa) = 2/e = .736$$

Also, the minimum value of $\phi(\kappa)$ is $\phi(1) = .736$.

Figure 3 gives computational results for the dependence of $\phi(\kappa)$ on κ.

EXAMPLES

As in reference 2 we consider two one inch thick target plates, one made of steel and the second made of titanium. We also consider two warhead types; the first involves 50 lbs of TNT at 300 feet standoff [3] while the second consists of a copper lined shaped charge fired under water, on which we found some data [2]. The values of κ and $\phi(\kappa)$ can be organized into the following table.

	Conventional κ, $\phi(\kappa)$	Copper Jet κ, $\phi(\kappa)$
Steel	5.38, 0.81	0.27, 0.78
Titanium	8.97, 0.84	0.45, 0.75

As Figure 3 makes clear, the maximum error in cutoff velocity cannot exceed 25%. Furthermore, the error is approximately twenty percent in the range of

interest. It therefore appears possible to assume that the true cutoff velocity v_c is approximately $.8v_N$ where v_N is the cutoff velocity calculated assuming no relief.

DISCUSSION

We have used a model problem to examine the error of a simple approximation obviating the calculation of the relief pressures used in the Doubly Asymptotic Approximation. The error is a function of $m/\rho c\theta$, which may be interpreted as the ratic of structural response times to fluid pressure decay times. The greatest relative error is about 27% and it occurs when $m/\rho c\theta = 1$. For practical examples involving steel, titanium, conventional warheads, and shaped charge warheads, it appears that the error is typically about 20%, suggesting a "correction factor."

The modest error of the present approximation in respect to cutoff velocity is of interest in its own right, particularly in the common case in which most of the energy available from the shock wave is transferred to the target plate before the true cutoff time. However, some energy is transferred to the target plate after cutoff by the fluid still flowing toward the plate. We hope to obtain a simple approximation for this part of the process in our future investigations.

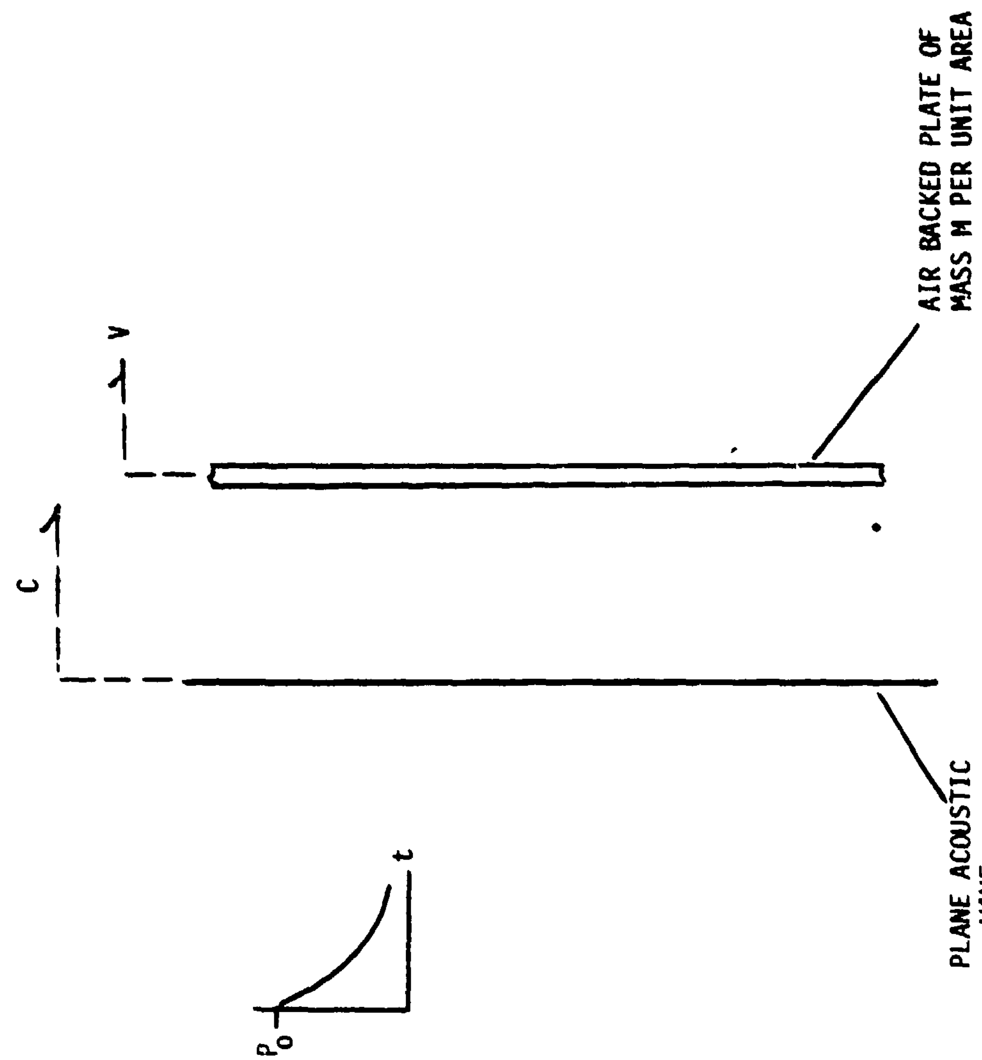

FIGURE 1 TARGET CONFIGURATION

$$\psi = \frac{\nu}{\kappa}\exp(-t)$$

$$\kappa W_r = \nu\kappa^{\frac{\kappa}{1-\kappa}}$$

$$\kappa W_N = \nu/(1+\kappa)$$

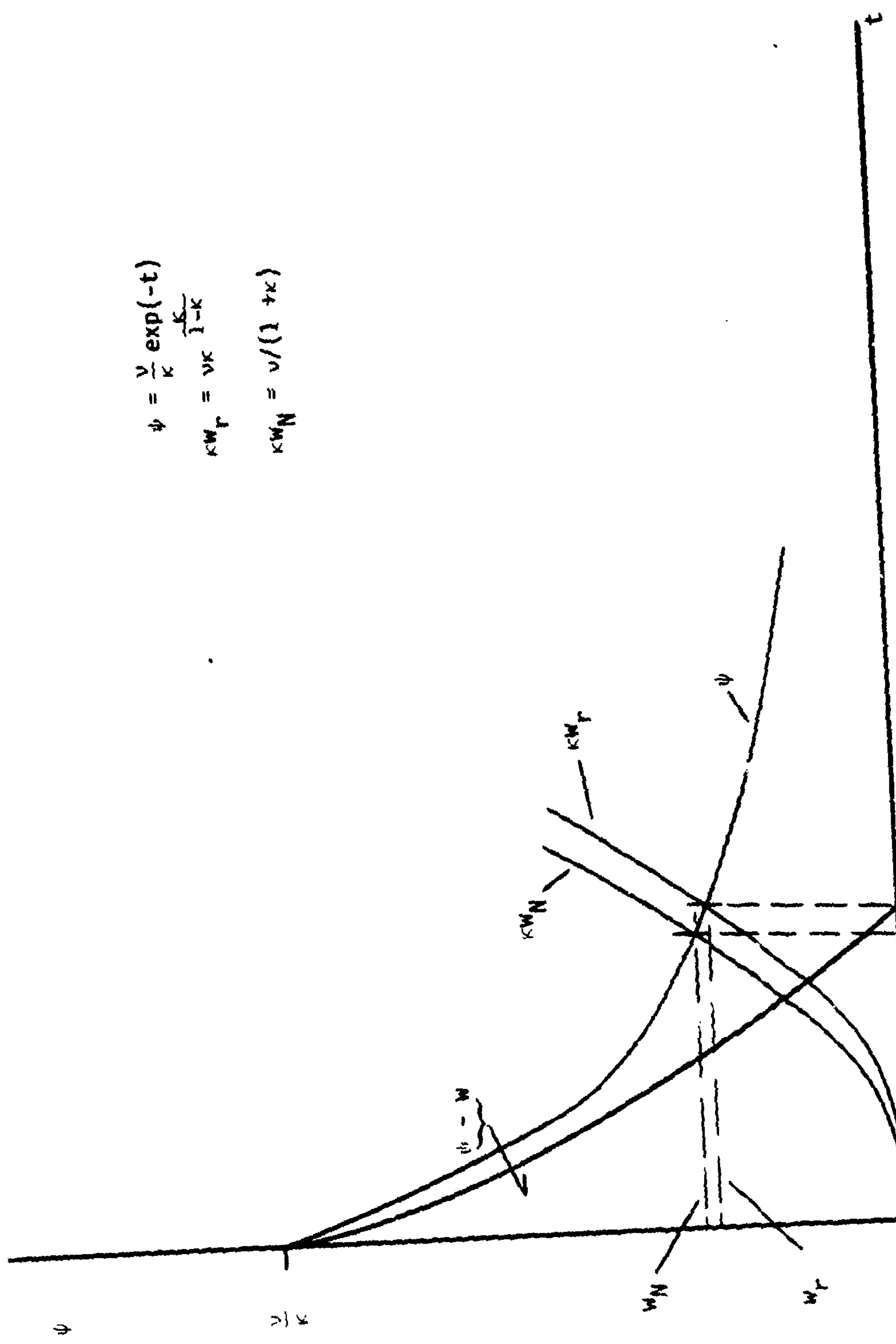

FIGURE 2 ILLUSTRATION ON CUTOFF

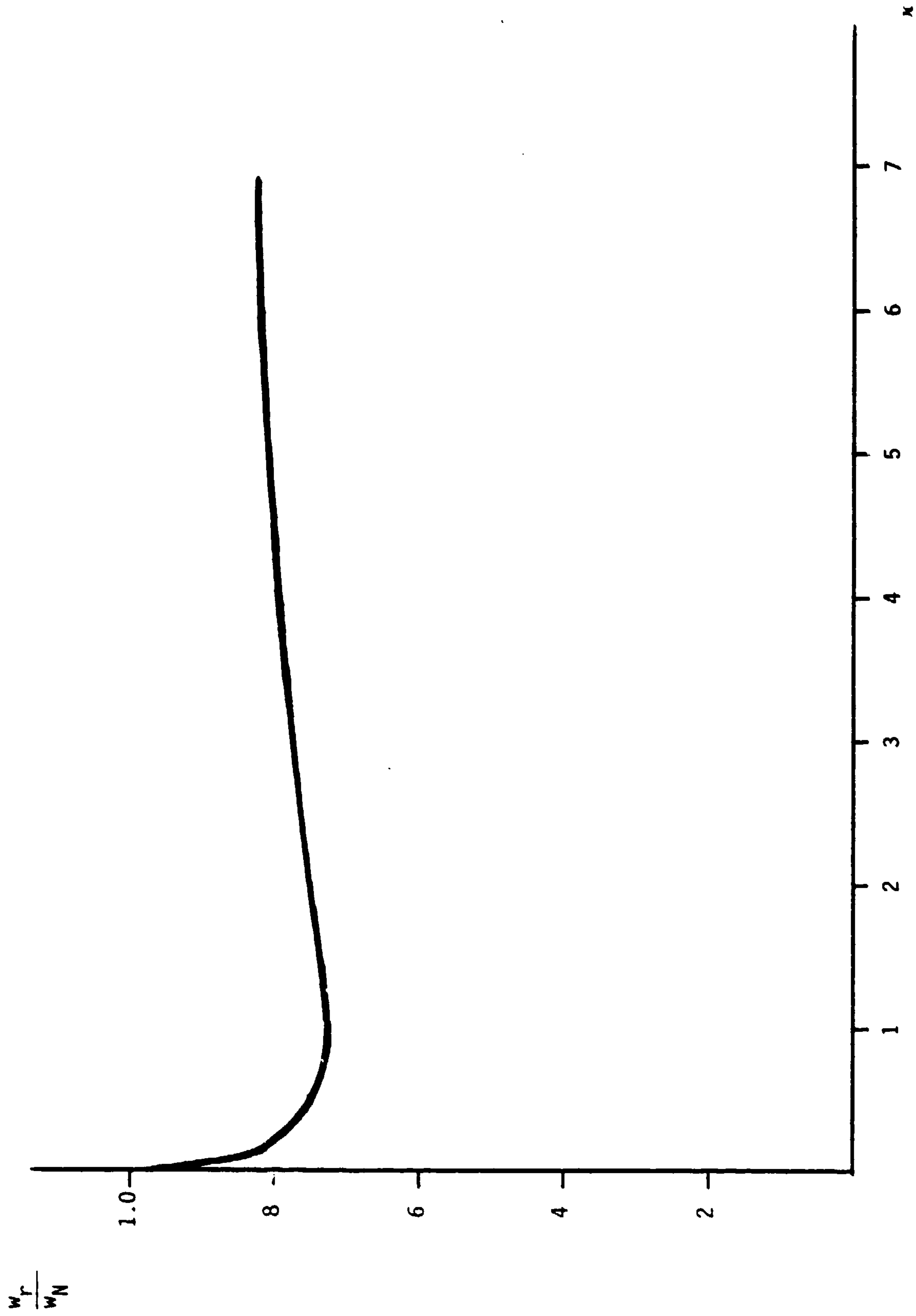

FIGURE 3 RATIO OF CUTOFF VELOCITY WITH RELIEF TO CUTOFF VELOCITY WITHOUT RELIEF

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